Effect of Transient Gasdynamic Processes on the Impulse of Pulse Detonation Engines

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Introduction

IN a pulse detonation engine (PDE), thrust results from the expansion of the high-pressure and temperature products of a detonation. Much of the effort in PDE development has been focused on the rapid initiation of detonation to achieve detonation in a distance compatible with the dimensions of an engine. The question of whether the impulse generated depends on different gasdynamic processes, such as direct initiation, deflagration to detonation transition (DDT), or constant volume explosion, becomes a valid one.

In the present study, the impulse produced by a single-cycle hydrogen–oxygen PDE is experimentally investigated. The goal is to determine the effect of transient gasdynamic processes on impulse. The impulse produced by direct initiation is compared to that produced by DDT for two different initiation locations, at the thrust wall and at the open end. The equivalence ratio is varied to control the run-up distance (RUD). The impulse is measured in two ways: the ballistic pendulum method and the integration of the end wall (thrust wall) pressure. The former, the ballistic pendulum method, was first applied to measuring the impulse generated by a detonation by Nicholls et al.[1] and has recently been used by Cooper et al.[2] and Daniau et al.[3] to measure the effect of obstacles and nozzles on the impulse generated by a single detonation pulse. Harris et al.[4] also used a ballistic pendulum to study the effect of nitrogen dilution and compared the impulse for the cases of direct initiation and DDT initiated from the closed end of the tube. In the ballistic pendulum technique, the amplitude of swing of a pendulum-mounted PDE provides a direct measurement of the total integrated thrust. The latter technique, integrating the end wall pressure, is more typically used in PDE experiments, but will only produce an accurate measurement of impulse if friction and other momentum losses are negligible.

Experimental Setup and Procedure

The experimental setup, as shown in Fig. 1, consisted of a smooth-wall stainless steel detonation tube 2.10 m long with a 6.35-cm inner diameter and closed at one end. The tube had a mass of 40 kg. It was equipped with 10 ports along its length to accommodate pressure transducers and ionization probes. Two pressure transducers measured both the end wall and open end pressure histories. The ionization probes recorded the time of arrival of the combustion front. The DDT process was initiated via a 30-mJ automotive-type spark plug, and the direct initiation was achieved via an exploding wire delivering up to 800 J. The igniter could be moved from the thrust wall to a port located 14.5 cm from the open end. The detonation tube was suspended by metal wires from supports located 2.635 m above the tube, and it was free to swing. A video camera captured the motion of the pendulum, from which the total specific impulse I_{sp} could be determined as follows:

$$I_{sp} = M_t/(g \cdot M_m) \cdot \left\{2g\left[L_w - \left(L_w^2 - X^2\right)^{\frac{1}{2}}\right]\right\}^{\frac{1}{2}} \qquad (1)$$

In Eq. (1), M_m is the initial mass of the mixture, M_t is the mass of the tube, L_w is the height of the supporting wires, g is the gravitational acceleration, and X is the horizontal displacement of the tube. The open end was sealed with a 0.0254-mm Mylar® diaphragm before each experiment. Control experiments were done with diaphragm thicknesses ranging from 0.023 to 0.254 mm, and no variation in impulse larger than the experimental scatter inherent to the experiment was observed. The tube was evacuated and filled with a hydrogen–oxygen mixture at ambient temperature and pressure by means of calibrated choked orifices. The tube was filled to 1 atm and then continuously flushed with 10 tube volumes of gas to ensure a uniform mixture. Before initiation, the hoses of the gas-handling system were disconnected from the tube to prevent interference with its motion.

Results and Analysis

By varying the equivalence ratio, the RUD could be varied. This distance (as measured from the ignition point) required for the flame to accelerate to a Chapman–Jouget (CJ) detonation, when initiated via a weak spark, is plotted in Fig. 2. A transition to detonation via DDT was only observed in this tube for equivalence ratios between $\Phi = 0.2$ and 1.8. The RUD did not vary when the location of the initiation was moved from the closed to the open end. In the case of the direct initiation via an exploding wire, the first velocity measurement in the tube was always the CJ velocity, and the detonation was assumed to form instantaneously. The propagation of the detonation and the blowdown process took place over a short period

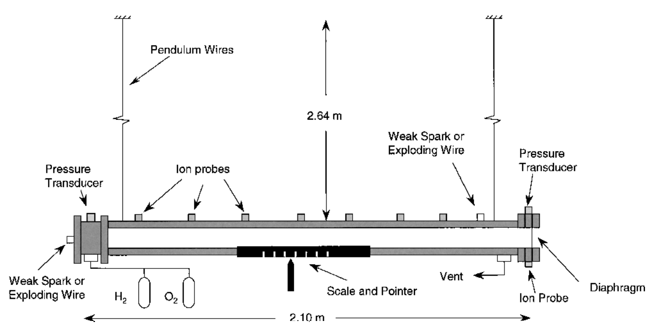

Fig. 1 Experimental setup showing igniter location for initiation at both the closed and open end.

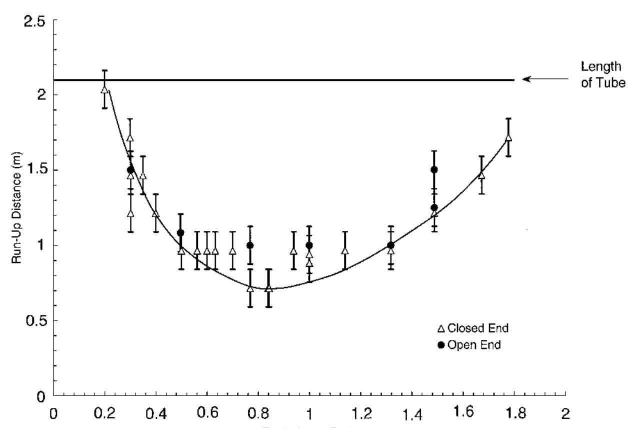

Fig. 2 RUD to detonation as measured from the point of initiation as a function of fuel equivalence ratio for the weak spark initiation from the closed and open end.

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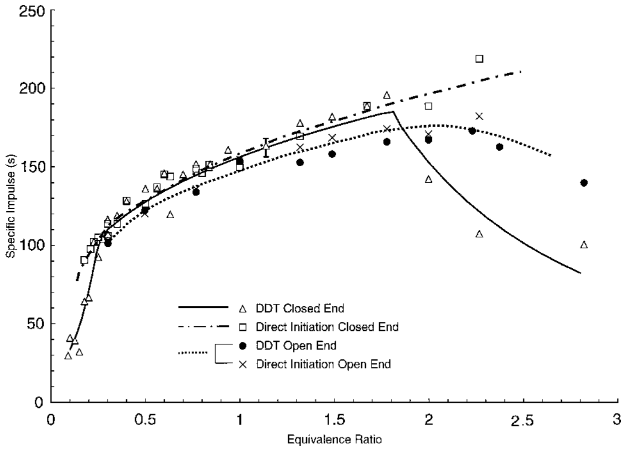
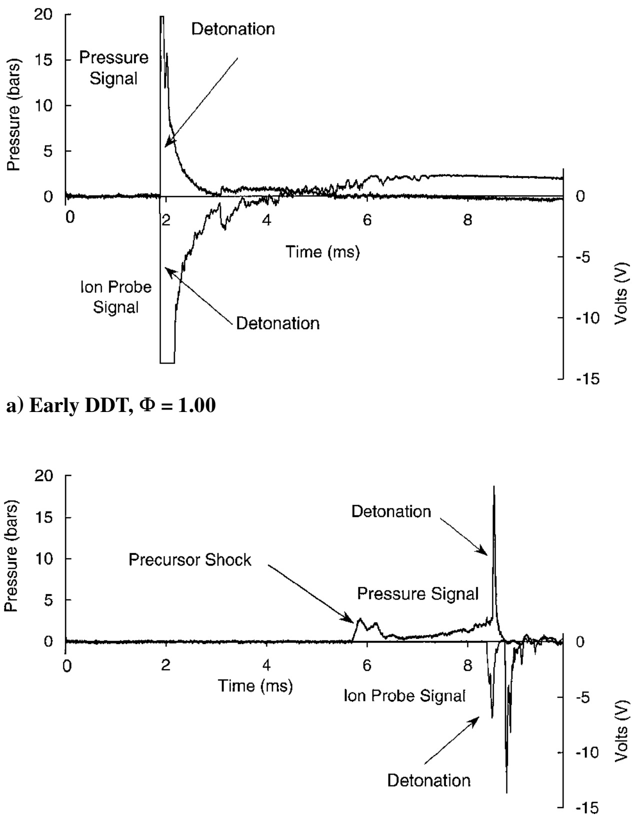


Fig. 3 Specific impulse as a function of fuel equivalence ratio for different initiation methods.



a) Early DDT, $\Phi = 1.00$

b) Late DDT, $\Phi = 0.17$

Fig. 4 Pressure transducer (positive signal) and ion probe (negative signal) records at the open end of the tube for the cases of a) early DDT and b) late DDT ignited at the closed end; note the presence of nonreacting precursor shock in case of late DDT.

of time (10–20 ms) when compared to the rise time of the tube (900–1000 ms). The momentum transfer to the tube was, thus, considered instantaneous for the four different gasdynamic processes studied.

Both impulse measurement techniques (ballistic pendulum and end wall pressure integration) exhibited good reproducibility, but the impulse from the pressure integration was consistently larger by 15–30%. Because the ballistic pendulum method takes into account all forces acting on the tube, the results obtained via this technique will be reported in this publication.

In Fig. 3, the I_{sp}, as measured by the ballistic pendulum technique, is plotted as a function of equivalence ratio. One typical error bar is presented ($\Phi = 1.2$) and is representative of the average experimental reproducibility. This is obtained from three to five experiments at the same conditions. For a fixed equivalence ratio, the energy content of the mixture is the same, and the comparison of the different initiation cases can be performed. Direct initiation and DDT at the closed end both produced the same impulse for equivalence ratios between $\Phi = 0.3$ and 1.8. For equivalence ratios below $\Phi = 0.3$ or above $\Phi = 1.8$, direct initiation at the closed end consistently produced more impulse than DDT. In this range ($\Phi < 0.3$ or $\Phi > 1.8$), DDT either occurred in the last quarter of the tube or did not occur in the tube at all. The presence of a precursor pressure wave ahead of the combustion front was verified by examining signals from the pressure transducer and ion probe located 1.5 cm from the open end of the tube as shown in Fig. 4. In the case of an early DDT (Fig. 4a) at an equivalence ratio of $\Phi = 1.00$, the first wave to encounter the diaphragm was a detonation wave, with the combustion front closely coupled to the leading shock. In Fig. 4b, the pressure signal for a late DDT at an equivalence ratio $\Phi = 0.17$ shows a precursor shock arriving 2.5 ms ahead of the main combustion front. This precursor compression wave, permitted by a late or absent DDT, ruptured the diaphragm before the arrival of the combustion front and resulted in the venting of unburned mass and a lower I_{sp}.

When the mixture was initiated from the open end, no significant difference between DDT and direct initiation was observed over the entire range of fuel equivalence ratio, as shown in Fig. 3. We note that the specific impulse from the initiation at the open end is consistently 15% lower than that of the initiation from the closed end (cf. Ref. 5). This difference is, however, of the order of the experimental scatter.

Conclusions

The impulse of a single-cycle PDE for different gasdynamic processes has been investigated. These different processes were obtained by varying the initiation method and location. The results show that when initiating from the closed end of the tube, the impulse produced by direct initiation and DDT is the same, as long as all of the mixture is burned inside the tube. This result agrees with the experiments of Harris et al.[4] using propane–oxygen mixtures. Initiation from the open end also exhibited an independence of the initiation technique (direct initiation vs DDT). The impulse generated by initiation from the open end is similar to the case of initiation from the closed end, as previously noted in the study by Zitoun et al.[5] that used integrated end-wall pressure to show the independence of the impulse on the point of initiation. In the present study, when initiating from the open end, the impulse appears to be slightly, but consistently, lower than that for the case of initiation at the closed end. These results strongly suggest that, to a first-order approximation, the impulse generated by a single cycle PDE is only a function of the chemical energy content of the combustible mixture and is independent of the details of the energy release mechanism.

Acknowledgments

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Supersonic Wave/Blade-Row Interactions Establish Boundary Conditions for Unsteady Inlet Flows

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THE computation of unsteady flows in high-speed airbreathing inlets requires a compressor-face boundary condition (CFBC). The physical basis for the analytical or numerical formulation of a realistic CFBC is the acoustic reflection coefficient of the operating compressor. In Ref. 1 an approximate, one-dimensional method is offered to calculate this information for a single blade-row compressor, when the total approach velocity (vector sum of axial and tangential components, relative to the rotor blades) is subsonic. The present Note extends the calculation to the practically important case where the total approach velocity is supersonic and the axial component is subsonic. (In this Note, the term "supersonic" refers to this limited range.) The background, motivation, physical model, method of analysis, and nomenclature described in Ref. 1 apply to this Note without change and are not repeated here. Familiarity with Ref. 1 is essential to the understanding of this Note.

In supersonic cascade flows expansion and compression waves can propagate upstream and can modify the approach flow, which makes them considerably different from subsonic cases. It has been well established[2,3] that a steady, uniform, supersonic flow upstream of an infinite, linear cascade of blades can exist only for a unique incidence angle. The existence of such an incidence implies that an upstream moving acoustic disturbance (which might be initiated by a downstream-moving disturbance arriving to the blade row) cancels the initial disturbance, restoring the undisturbed upstream flow. The unique incidence angle can be determined in the knowledge of the blade geometry and the upstream Mach number (methods given in Ref. 2). The unique incidence angle is generally small, several degrees only.

In the following, the exit Mach number is assumed to be subsonic, which is a practically common situation. This assumption also defines a unique steady flow when using the simple mean flow method of Ref. 1. The choice of subsonic outflow implies the presence of shocks (and, hence, a total pressure loss) in the blade passage. The effect of total pressure losses on the reflection coefficient is demonstrably small and a reasonable estimate is sufficient. Shock loss may be estimated as that associated with a normal shock at the upstream Mach number M_u. The estimation of viscous losses may be made on the basis of empirical information valid for similar blade geometries.

The analysis deals with a transient initiated by the arrival of an acoustic step change to the blade row, the goal being the prediction of the magnitude of the reflected wave, which is also a step change. The equations used in the present analysis are the same as those of Ref. 1, with one exception. In the subsonic case, it was assumed that the direction of the exit flow, after completion of the transient, is the same as the direction of the undisturbed exit flow [Eq. (25) in Ref. 1]. In the supersonic case, this requirement is dropped, and the unique incidence requirement is imposed on the entering flow. It is assumed that the response of the blade row has to be such as to restore the incidence angle (in region 3) to its original, unique value (in region 1). This assumption implies that

$$w'_{3y} = w'_{3x} \tan \beta_u \tag{1}$$

Because neither the incident nor the reflected acoustic wave can change the tangential velocity, the tangential velocity disturbances are zero in all upstream regions (1, 2 and 3). Equation (1) then forces the axial disturbance in region 3 to be zero also, which means that the region 3 velocity vector is identical to the undisturbed, region 1 velocity vector. The conclusion is that the imposition of Eq. (1) is equivalent to the assumption of constant (upstream) velocity. This is one of the traditional assumptions that has been applied in the past, without justification, to flows with any approach Mach number. The analysis of Ref. 1 showed that this assumption does not apply for a subsonic approach flow. The present analysis shows that the constant velocity condition is in fact applicable in the supersonic range.

The calculations are simple and are omitted. The acoustic wave coefficients are as follows:

$$\boldsymbol{A}_- \equiv \frac{p'_3 - p'_2}{p'_2} = 1 \tag{2}$$

$$\boldsymbol{A}_+ \equiv \frac{p'_4}{p'_2} = \frac{2M_{ux}\sqrt{\chi}}{\sigma(1 + M_{dx})} \tag{3}$$

The analysis also predicts a downstream-convecting vorticity wave. The corresponding vorticity induction coefficient is given by

$$\boldsymbol{V} \equiv \frac{\rho_u a_u w'_{4y}}{p'_2} = 2\frac{1 - \sqrt{\chi}M_{ux}/\lambda\sigma}{\sqrt{\chi}M_{dx}\tan\beta_d} \tag{4}$$

Equation (2) states that for supersonic flow the reflection coefficient is constant with a value of unity. This result is in excellent agreement with two-dimensional, inviscid Euler solutions obtained by Paynter to the same problem.[4] His solutions clearly indicate that for supersonic approach flows the reflection is such that the velocity direction in region 3 is the same as in region 1, in agreement with Eq. (1). Because $\boldsymbol{A}_-$ is independent of the mean flow properties, the mean flow parameters need not be known to compute this coefficient. In contrast, the calculation of the acoustic transmission and the vorticity induction coefficients does require the knowledge of all steady flow parameters, such as inlet Mach number, inlet/exit flow angles, passage height change, and loss coefficient.

The wave/blade interaction problems for stationary and moving blade rows are identical provided they are stated in coordinates fixed to the blades. If the inflow parameters are given in the stationary frame, then the solution process for a moving blade row consists of transforming all mean flow quantities to the blade-fixed coordinate system and subsequently calculating the wave coefficients using Eqs. (2–4).

For the special case of unloaded flat plates with no area change ($\beta_u = \beta_d = \beta$, $\chi = \lambda = \sigma = 1$, and $M_u = M_d = M$), the subsonic and transonic formulas both predict the same wave coefficients when $M = 1$, that is, the switch from the subsonic to supersonic behavior is continuous and occurs at $M = 1$. Figure 1 shows the variation of the reflection coefficient. Subsonic relations[1] are illustrated using thin lines in the plot whereas supersonic values are shown as thick lines. It is evident that, for subsonic flow, increasing Mach number increases the reflection amplitude. As M_{ux} is increased while keeping β_u constant, M_u becomes equal to one when $M_{ux} = \cos\beta_u$. For axial Mach numbers above this limit, the reflection coefficient is uniformly one for any value of β_u, as given by Eq. (2).

In the general case (curved blades, blade height change, nonzero total pressure loss), the switch from subsonic to supersonic regime involves a discontinuous change at $M_u = 1$ in the value of all three wave coefficients. Figure 2 shows the jump in transmission coefficients, for a representative set of mean flow parameters. Depending on the combination of parameters, the jumps can be significantly higher than those shown in Fig. 2.

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